

Verification and Validation of NASA-Supported Enhancements to Decision Support Tools of PECAD

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1.0 Introduction

This section summarizes the verification and validation (V&V) of recently implemented, NASA-supported enhancements to the decision support tools of the Production Estimates and Crop Assessment Division (PECAD). As previously discussed, the implemented enhancements include operationally tailored Moderate Resolution Imaging Spectroradiometer (MODIS) products and products of the Global Reservoir and Lake Monitor (GRLM). The MODIS products are currently made available through two separate decision support tools: the MODIS Image Gallery and the U.S. Department of Agriculture (USDA) Foreign Agricultural Service (FAS) MODIS Normalized Difference Vegetation Index (NDVI) Database. Both the Global Reservoir and Lake Monitor and MODIS Image Gallery provide near-real-time products through PECAD's CropExplorer. This discussion will address two areas:

1. Assessments of the standard NASA products on which these enhancements are based.
2. Characterizations of the performance of the new operational products.

2.0 V&V of Operationally Tailored MODIS Products

As mentioned above, two operationally tailored products are being provided to enhance PECAD's overall set of decision support tools: the CropExplorer MODIS Image Gallery and the USDA FAS MODIS NDVI Database. The CropExplorer MODIS Image Gallery is accessed through the CropExplorer interface and provides near-real-time access to processed MODIS image subsets. The CropExplorer MODIS Image Gallery is actually linked to a selected set of the imagery available through the Goddard Space Flight Center (GSFC) MODIS Rapid Response System. PECAD's decision support requirements related to near-real-time MODIS images are detailed in [Table 1](#).

Table 1. PECAD accuracy & delivery requirements for near-real-time imaging (NASA, 2004a).

| Category | Requirement |
|------------------|------------------------------------------------------------------|
| Product accuracy | Undetermined |
| Data time step | 1 day |
| Latency | 6 hours or less |
| Coverage | All land regions important for crop production and food security |

* To be evaluated in FY 2006.

In addition to quasi-global, near-real-time imaging, PECAD also requires a quasi-global NDVI image and time series database. Multi-day compositing is necessary for this product to reduce the impact of clouds, bidirectional reflectance distribution function effects, and other confounding factors. The requirements for an NDVI database as captured in the earlier decision support system evaluation are summarized in [Table 2](#).

Table 2. PECAD accuracy and delivery requirements for an NDVI database (NASA, 2004a).

| Category | Requirement |
|------------------|--------------------------------------------------------------------|
| Product accuracy | Must be consistent with existing NDVI database going back to 1981 |
| Data time step | 10 days* |
| Latency | 72 hours or less (measured from the end of the compositing period) |
| Coverage | All land regions important for crop production and food security |

* Considerable discussion has been held about this requirement since the release of the decision support system evaluation. At present this is not a firm requirement. Compositing intervals of 8, 10, and 16 days are under consideration.

Neither [Table 1](#) nor [Table 2](#) addresses spatial or geopositional requirements, which has been a matter of on-going discussion between PECAD and NASA. PECAD uses remote sensing data with ground sample distances (GSDs) ranging from less than a meter to multiple kilometers. For continuous regional monitoring, the MODIS GSD range (250–1000 m) has been judged to be sufficient, recognizing the necessary trades to achieve temporal requirements. However, field level analyses are not possible at this GSD range, so an idealized GSD would be tens of meters or less. Geopositionally, the PECAD need to perform temporal analysis and to cross-reference among several datasets implies a geopositional accuracy of one-half GSD or better.

2.1 Calibration and Validation of MODIS Sensor and Standard Products

The on-orbit calibration and validation of the MODIS sensor and standard MODIS products was dealt with comprehensively (for Terra MODIS) in a special issue of *Remote Sensing of Environment* in 2002. Several intrinsic properties of interest to operational users were characterized. Wolfe et al. (2002) reported a geolocational accuracy of 50 m (1σ) at nadir. For MODIS Bands 1 and 2 (the red and near-infrared bands used for PECAD tailored products), Rojas et al. (2002) found that the spatial response was consistent with prelaunch performance in the cross-track direction but was a bit degraded in the along-track direction. Huete et al. (2002) demonstrated that MODIS NDVI performed at higher fidelity than Advanced Very High Resolution Radiometer (AVHRR) NDVI. In a discussion of atmospheric correction for standard MODIS products, Vermote et al. (2002) showed a clear example of how not correcting for aerosol can dramatically affect the distribution of NDVI values throughout a scene.

Further work has been done regarding the cross validation of MODIS NDVI with other sensors. Gallo et al. (2004) found a linear relationship between AVHRR and MODIS 16-day composite time series with overall coefficient of variation (r^2) above 0.9 (considering 9 diverse land cover types). Working directly in support of the NASA/FAS partnership the Global Inventory Monitoring and Modeling Studies (GIMMS) group at NASA/GSFC has found similar results studying AVHRR, MODIS (MOD13 standard products), and SPOT VEGETATION (Justice, 2005). In Figure 1, NDVI time series are displayed from GIMMS estimates for one crop production region in South Africa and for another region in eastern Australia (the green line in each plot is MODIS Enhanced Vegetation Index, which is not used in current MODIS products tailored for PECAD). All of the NDVI time series have correlation coefficients above 0.9 relative to each other.

2.2 Characterization of the MODIS Operationally Tailored Products

The NDVI values in the USDA FAS MODIS NDVI Database are the same as the standard MODIS product NDVI values; the values are simply masked or summarized according to PECAD needs. Consequently, the standard MODIS NDVI validation work applies. Characterization of CropExplorer MODIS Image Gallery product accuracy is of questionable value because the final products are really pictures with visual as opposed to quantitative information content. As a result, the remainder of this section focuses on assessment of product performance in terms of delivery and coverage.

2.2.1 MODIS Product Delivery

The MODIS Rapid Response System product delivery was observed for 15 delivery days starting with June 23, 2005, (Julian day 173) through July 6, 2005 (Julian day 187). On July 2, 2005, an interruption of data lasted for more than 2 days. This problem affected all the data that was passed through the MODIS Rapid Response System to the CropExplorer MODIS Image Gallery and was reported on the MODIS Rapid Response System Status page (<http://rapidfire.sci.gsfc.nasa.gov/status/>) as shown in Figure 2.

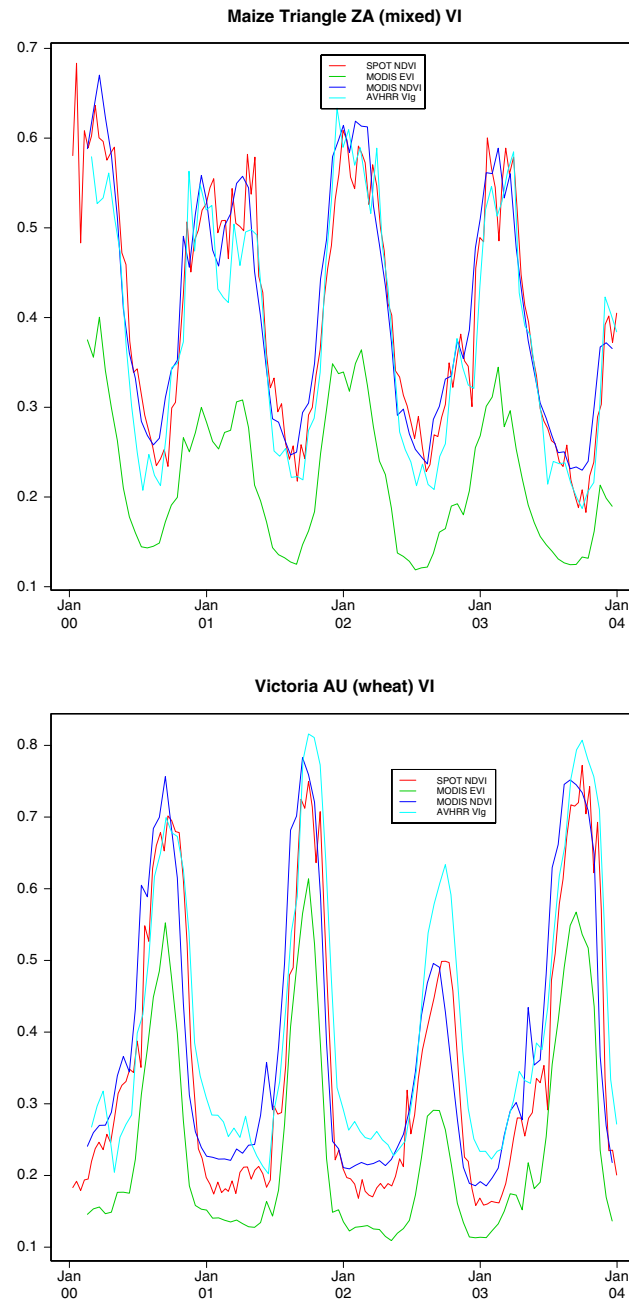


Figure 1. Vegetation index time series for the Maize Triangle region of South Africa and for the Victoria wheat-growing region of eastern Australia.

| Date | Description |
|-------------------------|------------------------------------------------------------|
| 2 July 2005 2005/183 | Some current data is not available due to hardware issues. |

Figure 2. July 2005 data interruption as reported on the MODIS Rapid Response System Status page.

Even five days after the July 2, 2005, interruption, the MODIS Rapid Response Delivery System delivery times were notably out of step with pre-interruption system performance, so only the first 10 days of observation were used to estimate “typical” system performance.

The estimated system latency for 59 tiles with an Aqua and a Terra delivery opportunity for each of 10 days (1180 distinct delivery opportunities) was 4.7 hours. The distribution of lag times was heavy tailed on the high side ([Figure 3](#)) with just over 65 percent of the MODIS Rapid Response System information available within the 6-hour requirement stated by PECAD and 80 percent within 24 hours. Even within the observed 10-day window, one significant interruption of delivery began on June 26 and ended on June 27. This event was not reported on the MODIS Rapid Response System Status page.

A systematic relationship existed between lag time and the time of day in which a particular subset-tile was acquired and processed. [Figure 4](#) shows that the lag time trend reaches a minimum of about 3 hours near 4:00 AM – 6:00 AM (UTC) and then rises slowly through the course of a day, reaching a maximum of more than 5 hours between 6:00 PM and midnight (UTC). The geographic distribution of delivery and lag times for Terra is shown in [Figure 5](#). The geographic distribution of delivery and lag times for Aqua is shown in [Figure 6](#).

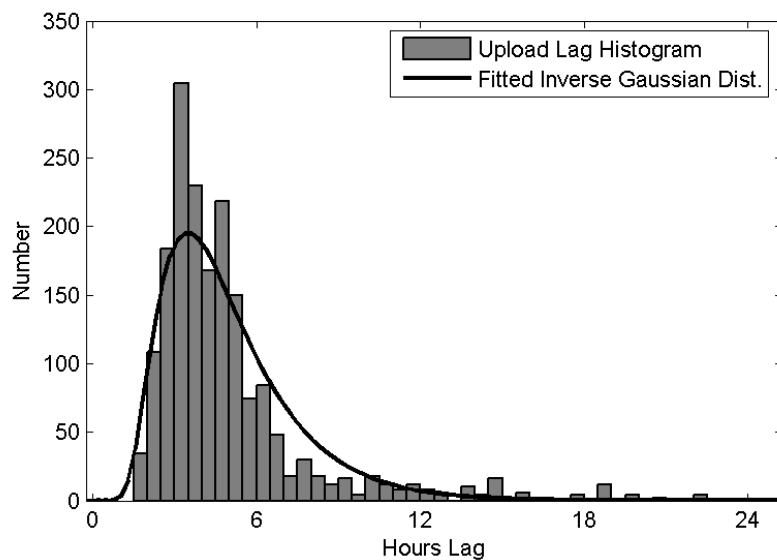


Figure 3. Distribution of CropExplorer MODIS Image Gallery delivery time lag from 23 June 2005 through 6 July 2005.

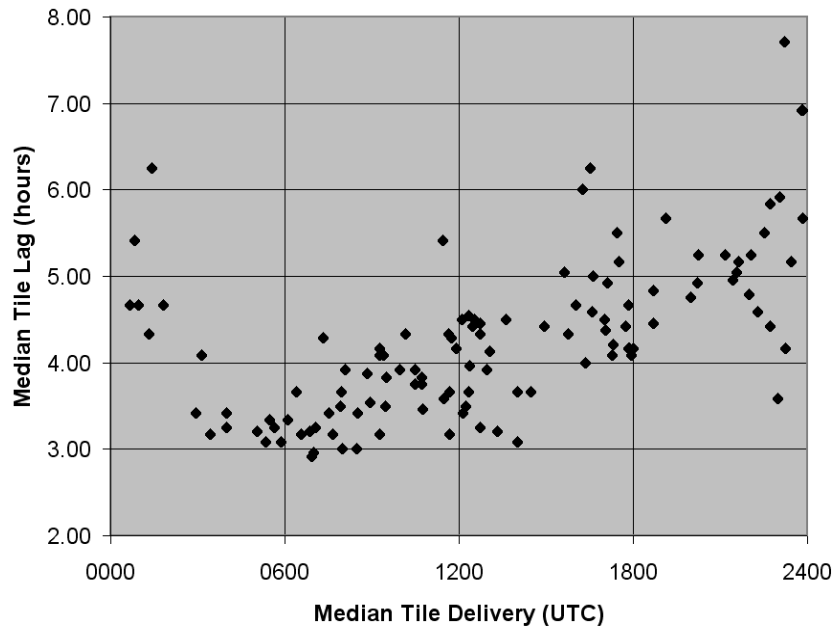


Figure 4. Variation of CropExplorer MODIS Image Gallery delivery time lag by time of day.

Taken as a whole, the CropExplorer MODIS Image Gallery latency is meeting the stated PECAD requirement of 6 hours. Nominally, the data time step is being met, but lapses in availability (both identified and unidentified in the MODIS Rapid Response System Status page) are a cause for concern.

The USDA FAS MODIS NDVI Database was not monitored in as careful a manner because it is more developmental in nature. However, it was observed that through June and July 2005, the shortest time lapse between end of compositing window and USDA FAS MODIS NDVI Database timestamp was about 9.5 days. This lapse has not yet met the project goal of 7 days, nor the PECAD goal of 72 hours stated in the DSS evaluation (NASA, 2004a). Given the 16-day time step and a latency of about 10 days (or more), the chance of PECAD analysts having more than one NDVI Database reading for the month leading to lock-up is small.

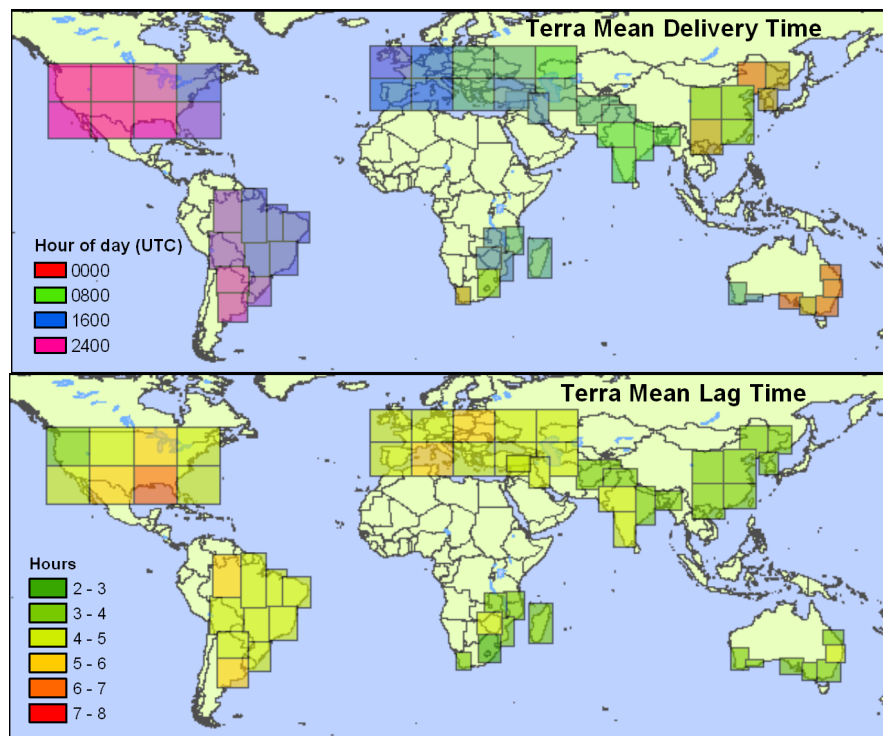


Figure 5. CropExplorer MODIS Image Gallery delivery and lag times for Terra.

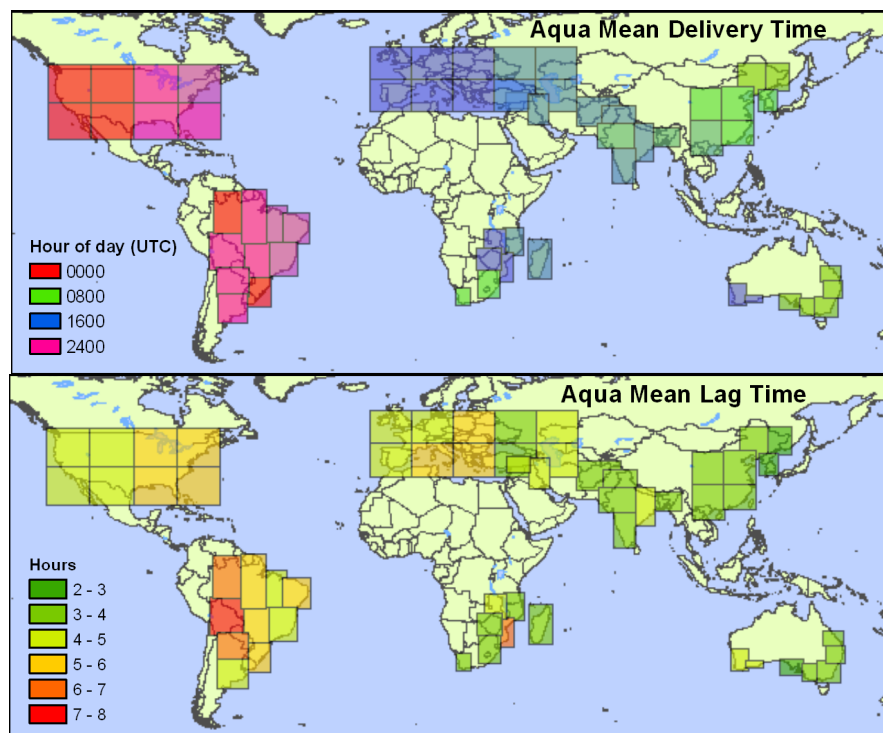


Figure 6. CropExplorer MODIS Image Gallery delivery and lag times for Aqua.

2.2.2 MODIS Product Coverage

The global footprints of the CropExplorer MODIS Image Gallery and the USDA FAS MODIS NDVI Database are shown in Figure 7. The USDA FAS MODIS NDVI Database essentially captures all of the economically important global crop production regions, but for some reason the Database omits a few regions of interest for food security including the Congo basin, the Horn of Africa, and Madagascar. The CropExplorer MODIS Image Gallery misses a few crop production areas of some economic importance including southeast Asia, parts of central Asia, Central America, parts of northern South America, and the northernmost productive region of the Great Plains of North America. Note that several subset-tiles have been added in northern Africa. These subset-tiles were not present at the beginning of the delivery time observation window, so they are not part of that analysis. Additionally, at the MODIS Rapid Response System site, subset-tiles are identified for FAS associated with Myanmar and southeast Asia that are not being passed through to the CropExplorer MODIS Image Gallery.

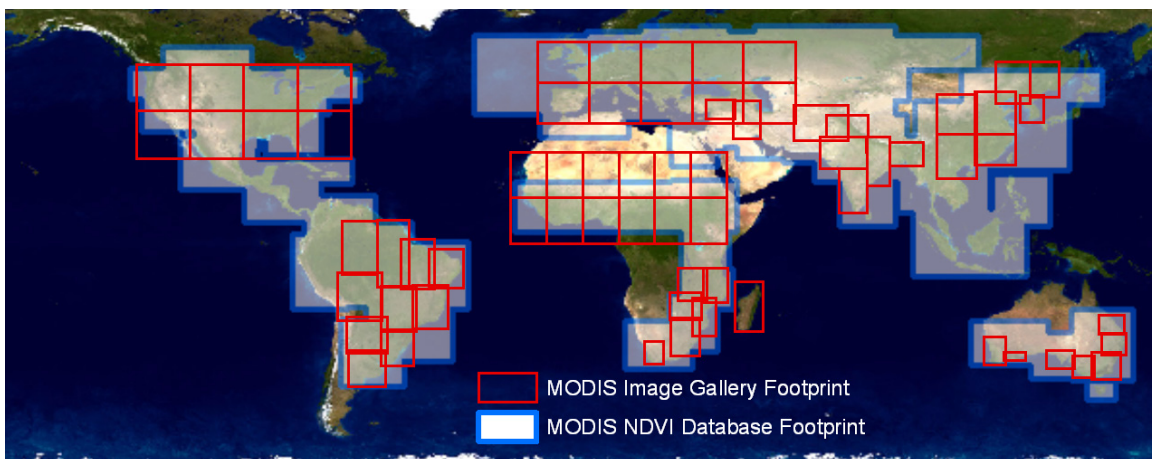


Figure 7. Comparison of CropExplorer MODIS Image Gallery and MODIS NDVI Database geographical footprints as of July 2005.

Overall, the MODIS operationally tailored products have nearly met the PECAD coverage requirements for economically important crop production, but important coverage gaps exist in terms of PECAD's food security mandate: most notably Central America and northern South America for the CropExplorer MODIS Image Gallery and the Congo basin for all MODIS products delivered to PECAD.

3.0 V&V of Global Reservoir and Lake Monitor Products

PECAD's decision support requirements related to surface water level variation are detailed in [Table 3](#).

Table 3. PECAD accuracy and delivery requirements for surface water level variation (NASA, 2004a).

| Category | Requirement |
|---------------------------------------|------------------------------------------------------------------------------------|
| Surface water level relative accuracy | 10 cm |
| Data time step | 10 days |
| Latency | 7–14 days |
| Coverage | Surface waters in all land regions important for crop production and food security |

3.1 Calibration and Validation of Jason-1 Radar Altimeter

Global Reservoir and Lake Monitor products are based on the measurements of the Jason-1 and TOPEX/Poseidon satellite radar altimeters (USDA, 2004). These are joint missions between NASA and the French space agency, the Centre National d'Etudes Spatiales (CNES). The primary purpose of these altimeters is to increase understanding of ocean surface topography. Their principal measurement is sea surface height (Ménard et al., 2003). The ranging approach for determining sea surface height differs in some particulars from the approach for determining surface water levels, but the two measurements are based on many common principles. Given that Jason-1 and TOPEX/Poseidon were designed for open sea measurements, the accuracy achieved by these instruments in measuring sea surface height sets the optimistic bound on accuracy that can be expected in measuring surface water levels.

After the launch of Jason-1 on December 7, 2001, about 10 months were dedicated to calibration of the new instrument and assessment of its performance. For much of that period, the Jason-1 and TOPEX/Poseidon satellites were operated in a common orbit with about one minute of separation between the two platforms, allowing an updated assessment of the TOPEX/Poseidon performance as well as a cross-validation between the two systems.

Three primary levels of distributed products were evaluated:

1. Geophysical Data Record (GDR) – final product based on ground processing, available in 30 days;
2. Interim Geophysical Data Record (IGDR) – intermediate products based on a preliminary orbit determination, available in 3 days; and
3. Operational Sensor Data Record (OSDR) – near-real-time products based on onboard processing, available in 3-5 hours.

Of these products, the GDRs and IGDRs are relevant to the Global Reservoir and Lake Monitor. The GRLM used GDRs for TOPEX/Poseidon data to establish historical data going back to 1992 and used IGDRs for Jason-1 data to provide a near-real-time product with a latency on the order of 10 days.

Ménard et al. (2003) summarized the Root-Sum-of-Squares (RSS) estimates of Jason-1 sea surface height errors as 3.3 cm for the GDR product and as 3.9 cm for the IGDR products. Working in diverse locations

including the Harvest platform near California (Haines et al., 2003), Corsica (Bonnefond et al., 2003), and the Bass Strait on the north side of Tasmania (Watson et al., 2003), the individual calibration/validation teams commissioned by CNES and NASA all achieved sea-based results consistent with the overall estimates. Each of these studies also measured TOPEX/Poseidon errors and found them to be in the same 3–4 cm range. Chambers et al. (2003) cross validated Jason-1 against TOPEX/Poseidon. Their estimates of individual sensor error were similar and they found the magnitude of the global bias between the sensors to be 14–15 cm. Residuals showed dependency on significant wave height, with local biases near coastlines and other more placid waters being somewhat lower and local biases in rougher waters being somewhat higher. This dependency on significant wave height accounts for some differences in bias estimates at the fixed sites, and it has implications for surface water level estimates since surface waters frequently have smaller wave heights than open ocean.

Further highlighting the challenge of altimetry over surface waters, one Jason-1 calibration/validation effort studied sea surface height as measured over the Great Lakes with a special focus on a specific calibration site on the Ohio shore of Lake Erie (Shum et al., 2003). After accounting for instrument bias, the Jason-1 residuals with Great Lake tidal gauges ran between 3 and 5 cm, which is consistent with other results. However, the relative bias between Jason-1 and TOPEX/Poseidon was estimated to be about 8 cm, which is 6 cm less than the global bias. Only a small portion of the difference could be attributed to wave height effects. Ultimately, the study could not explain the difference.

3.2 Characterization of the Global Reservoir and Lake Monitor

An initial verification and validation effort for the GRLM decision support tool was carried out in 2004 (NASA, 2004b). Though somewhat early in the implementation phase for the tool, this effort touched on all the requirements mentioned in [Table 3](#). Since the initial verification and validation effort was concluded, the tool has matured in terms of delivery and coverage, so requirements related to these properties were re-evaluated through the month of May 2005. As for the product accuracy requirement, the fundamental algorithm is essentially unchanged, so the results from 2004 will simply be summarized here. For further detail, refer to the online version of NASA 2004b.

3.2.1 GRLM Accuracy

The GRLM root mean square accuracy estimates over several North American lakes are summarized in [Table 4](#). Essentially, the Great Lakes can be considered representative of the larger water bodies in the GRLM. Great Lakes errors ran between 5 and 7 cm. Lake Winnebago and Lake of the Woods may be somewhat representative of smaller water bodies. Each estimate represents only a handful of potential readings per pass. Lake Winnebago error was calculated to be 27 cm and Lake of the Woods error was computed to be 26 cm. Lake Powell represents the most challenging type of lake or reservoir. The lake has very few potential readings per pass and it is surrounded by mountainous terrain. Lake Powell error over the period assessed was about 140 cm.

Note the Great Lakes errors computed for the GRLM are somewhat larger than those reported by Shum et al. (2003). This discrepancy may be explained by the earlier study's focus on the verification of sensor performance and by corrections for the sea surface height estimates being carefully tailored for the Great Lakes. The 2004 GRLM verification effort made no special corrections to the data because the focus of that study was the GRLM operational product accuracy.

Table 4. Verified GRLM performance over select North American surface water bodies.

| Water Body | Surface Area (www.worldlake.org) (km ²) | σ (outliers removed) (cm) | Passes Used in Assessment | Outlying Passes Removed |
|-------------------|----------------------------------------------------------------------------------------------------|-------------------------------------------|------------------------------|-------------------------------|
| Lake Superior | 82,100 | 7.3 | 81 | 0 |
| Lake Michigan | 57,800 | 5.3 | 75 | 0 |
| Lake Huron | 59,600 | 6.2 | 80 | 2 |
| Lake Erie | 25,700 | 6.5 | 73 | 1 |
| Lake Ontario | 18,960 | 4.5 | 79 | 3 |
| Lake Winnebago | 557 | 27.0 | 24 | 0 |
| Lake of the Woods | 1,900 | 26.1 | 42 | 1 |
| Lake Powell | 500 | 140.6 | 244 | 6 |

NOTE: All lakes and reservoirs were characterized using Jason-1 IGDR-based estimates with the exception of Lake Powell. No Jason-1-based estimates existed for Lake Powell as of May 2004, so TOPEX/Poseidon GDR-based estimates were used.

While not all lakes meet the stated FAS accuracy requirement, perhaps the accuracy requirement should be revisited. For deep, narrow reservoirs, fairly large height uncertainty may be acceptable because the information regarding water volume is still readily discernable. For shallow, closed lakes (e.g., Lake Chad), the current standards are appropriate. Furthermore, FAS lake water height requirements should be developed in more detail to include a comprehensive listing of water bodies that FAS believes should be monitored.

3.2.2 GRLM Delivery

The latency of the GRLM products decreased from 10.3 days to 5.8 days between May 2004 and May 2005. Latency was defined as the mean lag time between data acquisition and GRLM product upload. The maximum lag time in May 2004 was 19.2 days, but in May 2005 the maximum lag time was reduced to 10.4 days. This dramatic improvement in delivery time was accomplished by reducing the average time between GRLM updates from 16 days to 6 days. This improvement clearly meets the stated FAS 10-day latency requirement for surface water level variation.

GRLM delivers data for every Jason-1 pass that has a 9.9-day period, so the FAS 10-day time step requirement is nominally met. However, for various reasons, over many lakes and reservoirs the Jason-1 standard product algorithms yield no height information for some passes. For many instances in both 2004 and 2005, months or even years passed between instances in which water levels were actually estimated. These dated sites have archival value, but they no longer provide information about current regional water availability. A breakdown of the time to last estimated water level is shown in [Figure 8](#).

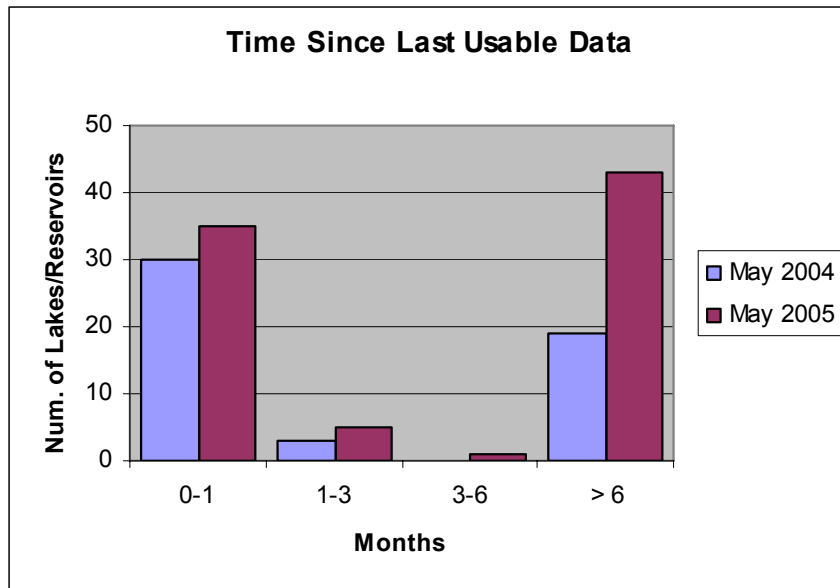


Figure 8. Histogram of time to last estimated water level checked at the end of May 2004 and again at the end of May 2005.

From May 2004 to May 2005, the number of lakes and reservoirs being monitored increased over 60 percent from 52 to 84. An incremental increase occurred in the number of water bodies with near-real-time monitoring, but most of the increase consisted of lakes and reservoirs that have had little or no valid data since Jason-1 became operational. Much of the difficulty stems from the fact that more near-land data is being filtered by new algorithms implemented for standard Jason-1 data processing. Although some indication was noted that this problem was being addressed in the fall of 2004 (NASA, 2004b), little or no positive impact seems to have occurred. The geographic distribution of which sites are more current and which sites are more out of date is shown in [Figure 9](#).

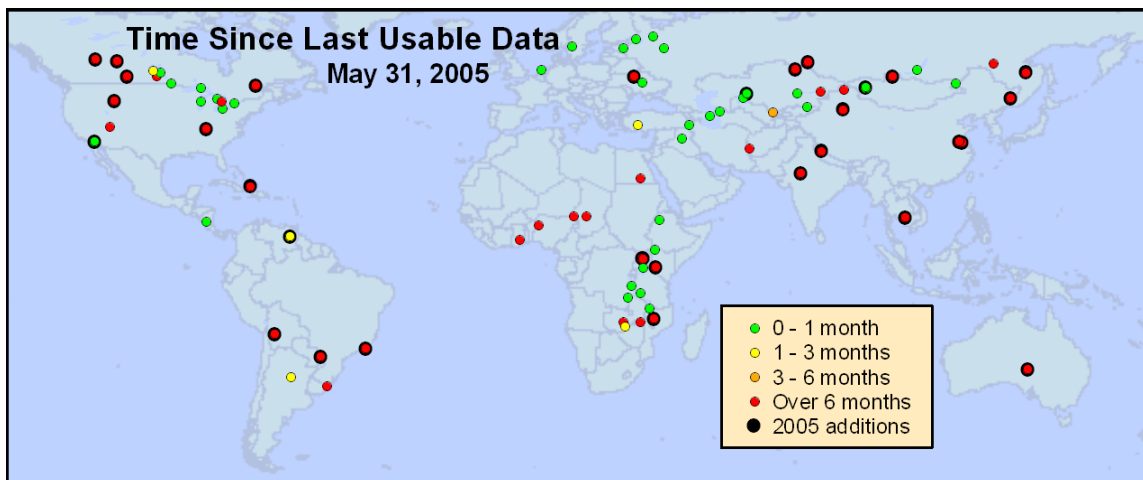


Figure 9. Geographic distribution of time to last estimated water level at the end of May 2005.

3.2.3 GRLM Coverage

In 2004, little coverage existed in South America, western North America, or eastern Asia. Australia had no monitored sites. As can be seen in [Figure 9](#), through May 2005 sites have been added in all of these areas. Unfortunately, the overwhelming majority of the new sites are badly dated, so the near-real-time coverage has changed little.

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5.0 Acronyms

| | |
|-------|--------------------------------------------------------------|
| AVHRR | Advanced Very High Resolution Radiometer |
| CNES | Centre National d’Etudes Spatiales (the French space agency) |
| FAS | Foreign Agricultural Service |
| GDR | Geophysical Data Record |
| GIMMS | Global Inventory Monitoring and Modeling Studies |
| GRLM | Global Reservoir and Lake Monitor |
| GSD | ground sample distance |
| GSFC | Goddard Space Flight Center |
| IGDR | Interim Geophysical Data Record |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| NDVI | Normalized Difference Vegetation Index |
| OSDR | Operational Sensor Data Record |

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|-------|---------------------------------------------------|
| PECAD | Production Estimates and Crop Assessment Division |
| RSS | Root-Sum-of-Squares |
| USDA | U.S. Department of Agriculture |
| V&V | Verification and Validation |

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| 13. SUPPLEMENTARY NOTES | | | | | |
| 14. ABSTRACT <p>This section of the evaluation report summarizes the verification and validation (V&V) of recently implemented, NASA-supported enhancements to the decision support tools of the Production Estimates and Crop Assessment Division (PECAD). The implemented enhancements include operationally tailored Moderate Resolution Imaging Spectroradiometer (MODIS) products and products of the Global Reservoir and Lake Monitor (GRLM). The MODIS products are currently made available through two separate decision support tools: the MODIS Image Gallery and the U.S. Department of Agriculture (USDA) Foreign Agricultural Service (FAS) MODIS Normalized Difference Vegetation Index (NDVI) Database. Both the Global Reservoir and Lake Monitor and MODIS Image Gallery provide near-real-time products through PECAD's CropExplorer. This discussion addresses two areas:</p> <ol style="list-style-type: none"> 1. Assessments of the standard NASA products on which these enhancements are based. 2. Characterizations of the performance of the new operational products. | | | | | |
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